

Structure of the Radio Source 3C 120 at 8.4 GHz from VLBA+ Observations in 2002

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Abstract — Abstract—Maps of the radio source 3C 120 obtained from VLBA+ observations at 8.4 GHz at five epochs in January–September 2002 are presented. The images were reconstructed using the maximum entropy method and the Pulkovo VLBIImager software package for VLBI mapping. Apparent superluminal motions of the brightest jet knots have been estimated. The speeds of jet knots decreases with distance from the core, changing from $5.40 \pm 0.48c$ to $2.00 \pm 0.48c$ over 10 mas (where c is the speed of light) for a Hubble constant of $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This can be explained by interaction of the jet with the medium through which it propagates.

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1. INTRODUCTION

The hypothesis that the jets in quasars and active galactic nuclei are associated with the energy released by the accretion of matter onto a central black hole via an accretion disk is strongly supported by observations of microquasars in our own Galaxy [1]. Radio observations of microquasars display apparent superluminal motions of bright jet components that appear after a sharp dip in the X-ray radiation, believed to be due to a loss of the accretion stability.

The first extragalactic source in which such processes were detected was the active radio galaxy 3C 120 (redshift $z = 0.033$), whose X-ray and radio emission displays behavior similar to that observed in microquasars. Marscher et al. [2] showed that, after X-ray dips, superluminal ejections propagate in the radio jets of 3C 120 with apparent speeds from $4.1c$ to $5.0c$, where c is the speed of light, for a standard cosmological model with a Hubble constant of $65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In this case, the distance to 3C 120 is 140 Mpc, and 1 mas corresponds to a projected distance of 0.70 pc. The study [2] was carried out using VLBA+ observations at 43 GHz from November 1997 to April 2001 (16 epochs in total).

In the current paper, we analyze the structure of the radio galaxy 3C 120 based on VLBA+ observations for five epochs in January–September 2002 at 8.4 GHz and estimate the apparent speeds of the brightest knots in the jet. The mapping employed the Maximum Entropy

Method (MEM), enabling us to obtain superresolved images, and thereby trace the motion of the brightest knots in the jet with higher accuracy.

2. DATA

General information on the radio galaxy 3C 120 is given in Table 1. The observational data we used, obtained on the VLBA+ network, were retrieved from the NRAO archive (USA). Information on these observational data, obtained at five epochs from January to September 2002, is given in Table 2. The VLBA+ network includes the 10 stations of the Very Long Baseline Array (VLBA) together with several stations of the global VLBI network. The stations in Table 2 are given as two-character codes, whose full names can be found at the site http://www/evlbi.org/proposals/2_lett_station_codes.txt. The filling of the UV (spatial frequency, or baseline) plane and the visibility amplitude as a function of the baseline length projected onto the UV plane are given in Fig. 1.

3. DATA-PROCESSING TECHNIQUES

The data were processed using the Pulkovo software package for VLBI mapping VLBIImager, which was developed by one of the authors of

this paper. The images were constructed using self-calibration [3] in combination with MEM as the deconvolution procedure [4, 5]. Our choice of MEM as the deconvolution algorithm is based on our desire to obtain superresolution under the condition that the solution display the maximum smoothness. This makes it possible to study finer structure in the source, and to determine the coordinates of jet knots to higher accuracy [3]. We also used the well-known technique of Gaussian model fitting [3] to find the positions of jet knots. The errors in the coordinates were estimated using the Monte-Carlo method, by varying the source spectra within preset limits determined by the errors in the visibility function [3].

4. RESULTS

Figure 2 presents maps of 3C 120 obtained by convolving the MEM solutions with the “clean” beams indicated in the lower left corner of each map. The contour levels on all maps in this paper are 0.5, 1, 2, 4, 8, 16, 32, 64, and 90 % of the peak value. The parameters of the maps are listed in Table 3. Figures 3a and 3b show the variations with epoch of the peak and total flux densities in the radio maps. Note that the maps in Fig. 2 are in good consistency with maps obtained from the same data using various software packages (DIFMAP, AIPS; see the site <http://rorf.usno.navy.mil/RRFID/>).

However, we are more interested in the direct MEM solutions, which have a considerably higher resolution, and so display finer features in the maps, while simultaneously being maximally smooth, in accordance with the criterion of the maximum-entropy method.

Figure 4 presents the MEM images of 3C 120, arranged from top to bottom in time order; the separations between the maps are proportional to the time differences between the epochs. The positions of four distinct knots in the jet (labelled A1, A2, A3, and A4) are shown. Straight lines drawn from top to bottom and connecting corresponding knots at different epochs show their trajectories.

Table 4 lists the distances of these jet knots from the core, labelled C in Fig. 4. The upper limit of the error in the distances estimated via the Monte-Carlo method is approximately ± 0.1 mas, and we will use this as the maximum uncertainty in the individual distances of the jet knots. The obtained coordinates for components A1, A2, A3, and A4 as functions of the epoch can be used to estimate their apparent speeds. The proper motions in mas/year and corresponding speeds in units of the speed of light for a standard cosmological model with cold dark matter (Λ CDM) and a Hubble constant $H = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are presented in Table 5. Figure 5 shows a graphical representation of the motions of

the components. Their apparent speeds as functions of distance from the core are shown in Fig. 6. Our derived speeds for components A1 and A2 (the closest to the core) are consistent with the results of [2], while the motions of the more distant components A3 and A4 are slower.

Thus, Fig. 6 demonstrates that the jet components do not move at constant speeds: the closer the component to the core, the higher its speed. On scales out to 10 mas (corresponding to 7 pc for the adopted cosmology), the component speeds vary from $(5.40 \pm 0.48)c$ to $(2.00 \pm 0.48)c$. We took into account the error corridor of ± 0.1 mas for the straight lines shown in Fig. 5 when estimating the uncertainties of these superluminal speeds. The deceleration in the component speeds with distance from the radio core can be explained by interaction of the jet with the medium through which it propagates: the deceleration will be more noticeable the lower the emission frequency (the greater the distance from the core). Therefore, the distance dependence of the jet component speeds is much less pronounced in the 43-GHz maps [2].

5. CONCLUSION

Our study of the structure of the radio galaxy 3C 120 in the period from January to September 2002 based on VLBA+ observations at 8.4 GHz has allowed us to determine apparent superluminal speeds for the brightest knots in the extended jet on scales out to 7 pc for a standard cosmological model with cold dark matter and a Hubble constant of $H = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We find that the apparent speeds of the jet components are not constant, and depend strongly on the distance from the radio core: the speed decreases with increasing distance from the core. The apparent speeds of the brightest jet knots decrease from $(5.40 \pm 0.48)c$ to $(2.00 \pm 0.48)c$, where c is the speed of light. This deceleration can be explained by interaction of the jet with the medium through which it propagates.

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Table 1. General information about 3C 120

Alias	Right ascension (J2000)	Declination (J2000)	Total flux density at 5 GHz, Jy	Optical counterpart	Redshift
J0433+0521	4h 33m 11.0955s	+5° 21′ 15.62″	3.8	galaxy	0.033

Table 2. The VLBA+ observations of 3C 120

No.	Date Epoch	Frequency, MHz	Polarization	Number of stations	Station names	Number of measurements
1.	16.01.2002 2002.044	8409.97	RCP	18	BR,FD,GC,HN,KP,LA,MC, MK,NL,NY,ON,OV,PT,SC, TS,WF,KK,WZ	4287
2.	06.03.2002 2002.178	8409.97	RCP	18	BR,FD,GC,HN,KP,LA,MC, MK,NL,NT,ON,OV,PT,SC, TS,WF,KK,WZ	4784
3.	08.05.2002 2002.351	8409.97	RCP	17	AR,BR,FD,GC,HH,HN,KP, LA,MA,MC, NL,OV,PT,SC, WF,KK,WZ	5682
4.	24.07.2002 2002.562	8409.97	RCP	15	BR,GC,HN,KP,LA,MA,MK, NL,NY,OV,PT,SC,TC,WF,KK	16556
5.	25.09.2002 2002.734	8409.97	RCP	15	BR,FD,GC,KK,KP,LA,MA, MC,MK,NL,ON,OV,PT,TS,WZ	1186

Table 3. Map parameters as functions of the epoch

Epoch	Clean beam size (FWHM), (mas× mas)	Peak flux density, Jy/beam	Total flux density, Jy
2002.044	1.71×0.63,-5.63°	0.48	1.88
2002.178	1.93×0.66,-1.88°	0.64	2.39
2002.351	1.75×0.94,10.80°	1.09	2.52
2002.562	1.65×0.82, 5.53°	0.91	2.07
2002.734	1.50×0.80, 0°	0.79	1.71

Table 4. Distance r from the core to the jet knots A1–A4

Эпоха	A1	A2	A3	A4
2002.044	1.79	4.22	5.91	8.67
2002.178	2.26	4.12	–	8.73
2002.351	–	4.49	6.35	8.92
2002.562	3.00	5.21	–	–
2002.734	–	5.38	–	–

Table 5. Apparent speeds of the jet knots

Jet knot	Proper motion mas/year	Speed, c
A1	2.24±0.20	5.38±0.48
A2	1.96±0.20	4.70±0.48
A3	1.43±0.20	3.43±0.48
A4	0.83±0.20	1.99±0.48

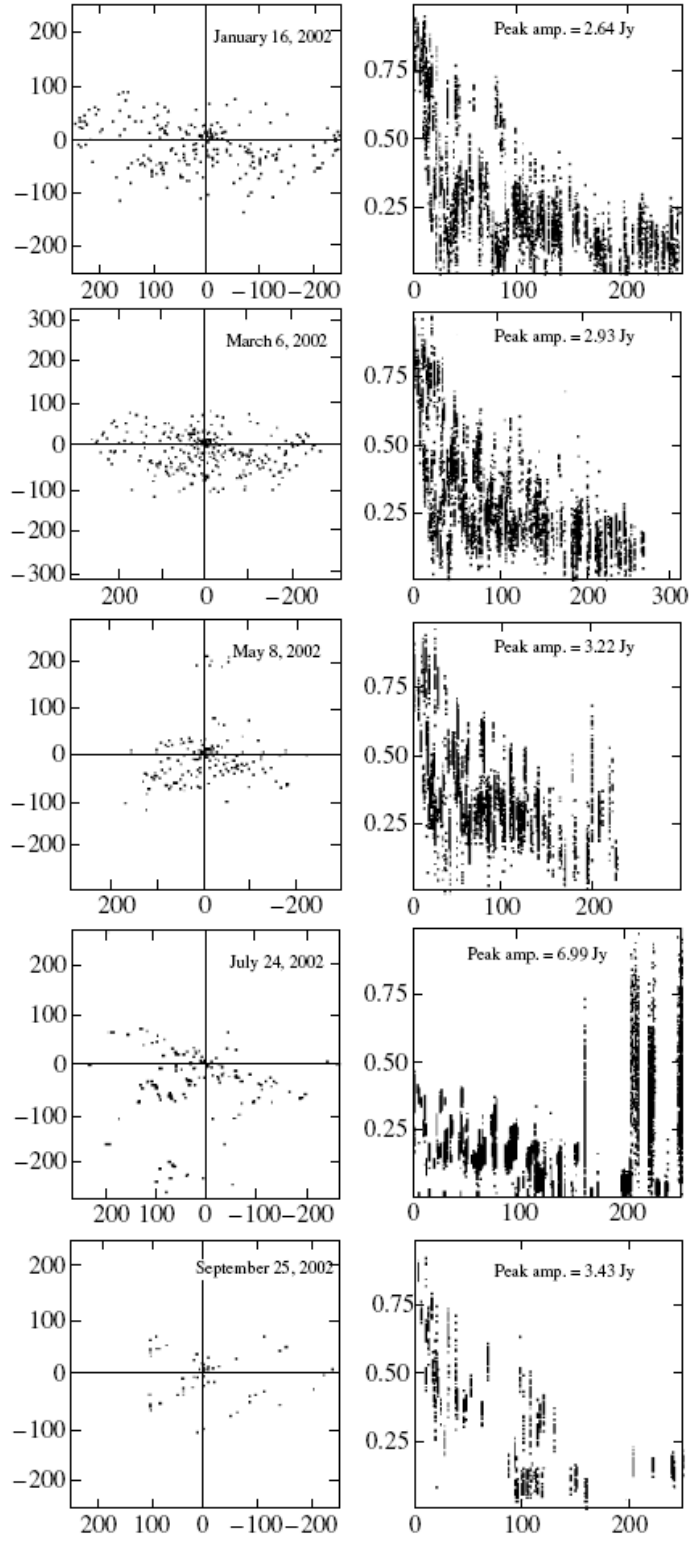


Fig. 1. Left: Coverage of the UV (spatial-frequency, or baseline) plane. The horizontal and vertical axes show the U and V baseline components in units of 106 wavelengths. Right: Amplitude of the visibility function (in relative units) as a function of the projected baseline length in units of 106 wavelengths for the five epochs of observations. The peak amplitudes in Jy are given on the graphs.

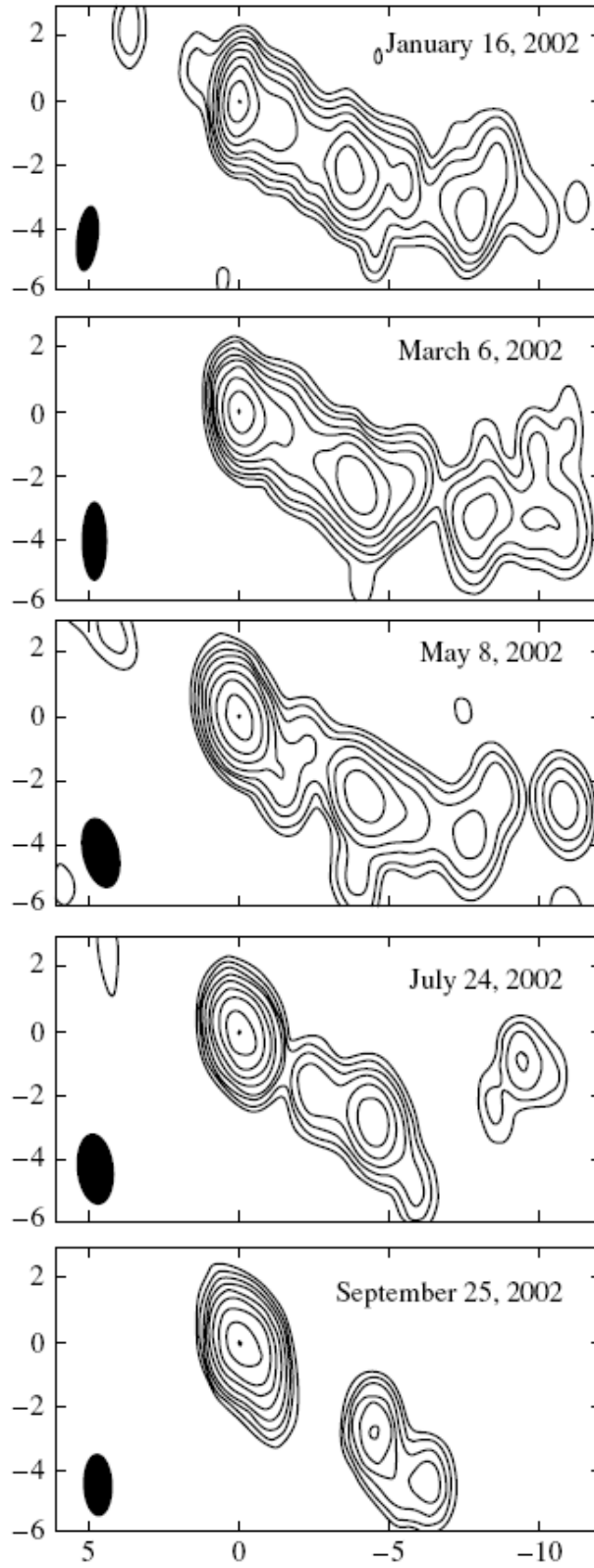


Fig. 2. Maps of 3C 120 obtained by smoothing the MEM solution using the “clean” beams shown in the lower left corners of the maps. The horizontal and vertical axes show relative right ascension and declination in mas.

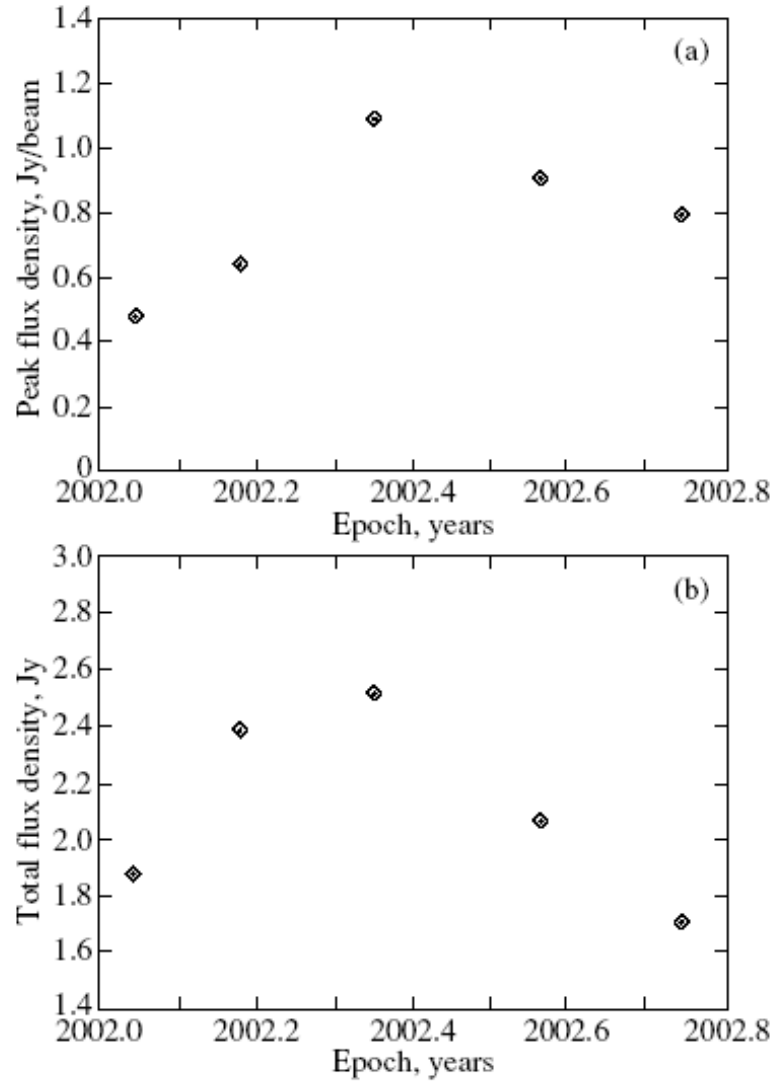


Fig. 3. (a) Peak and (b) total flux densities in the maps as a function of the observing epoch.

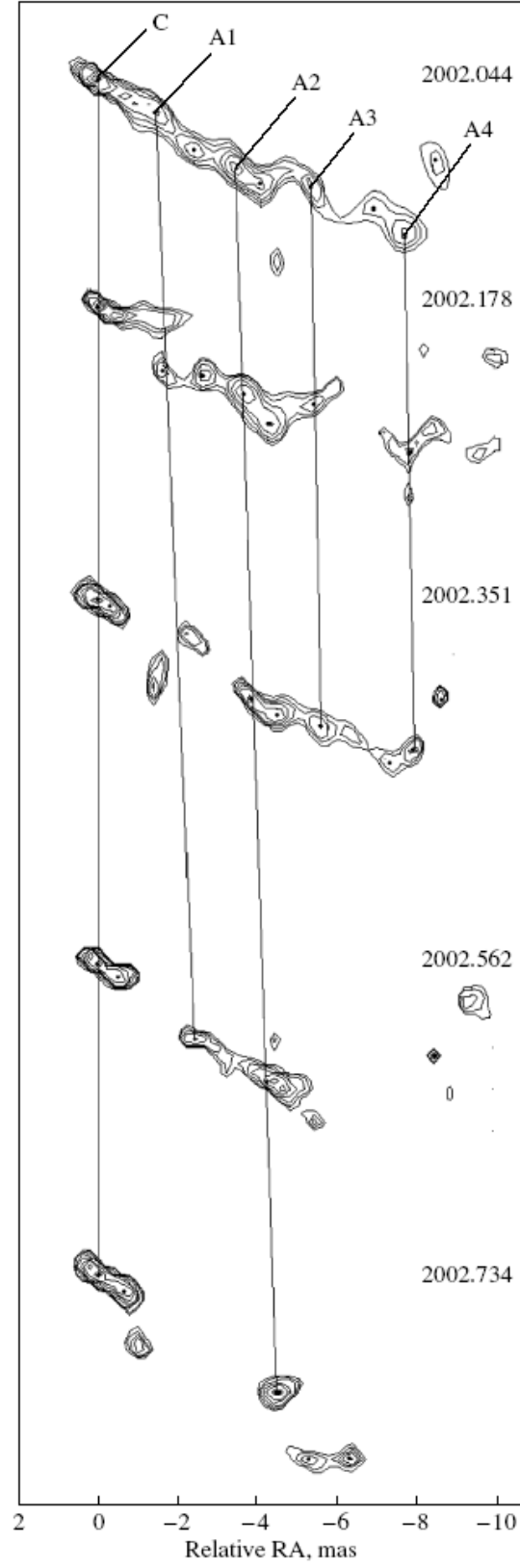


Fig. 4. Sequence of high-resolution MEM maps arranged from top to bottom in time order. The distances between the map phase centers are proportional to the time differences between the epochs. The straight lines connecting the centers of the jet knots (labelled A1–A4) show their trajectories.

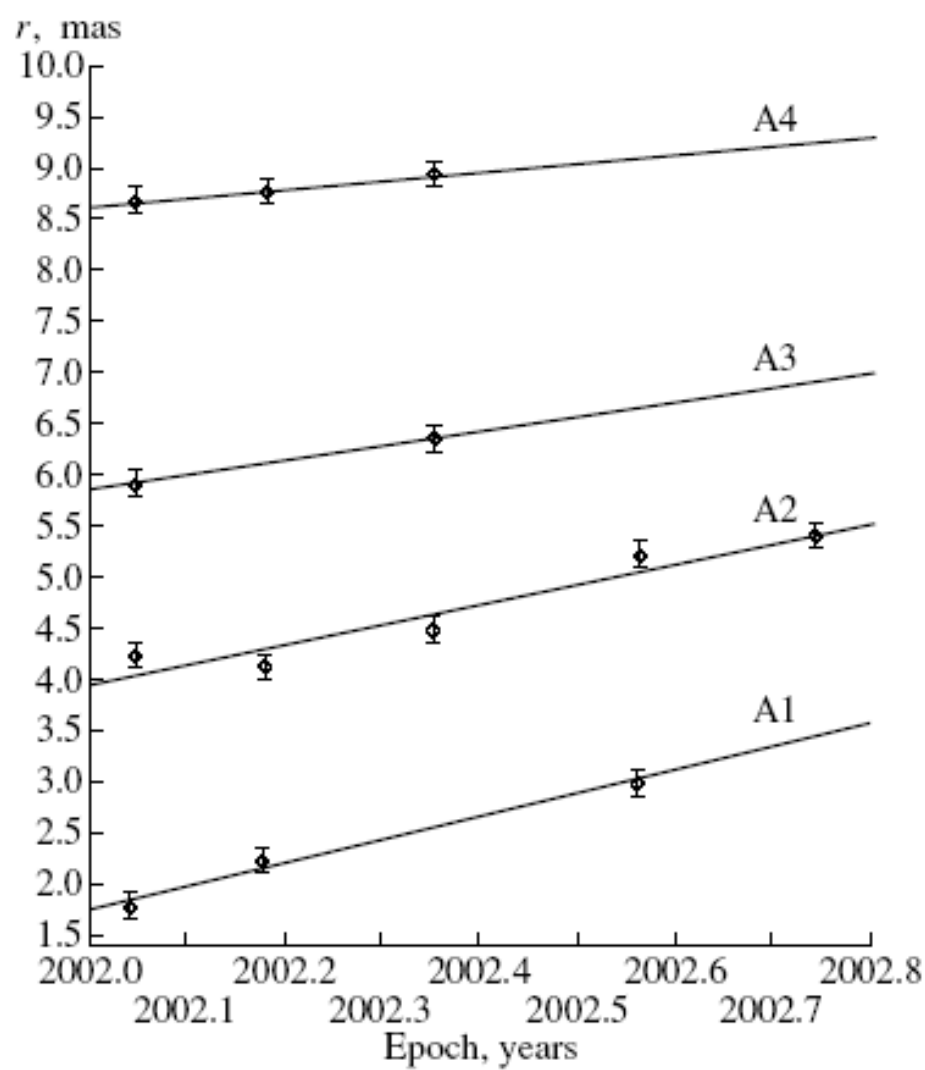


Fig. 5. Apparent motions of the jet knots A1–A4.

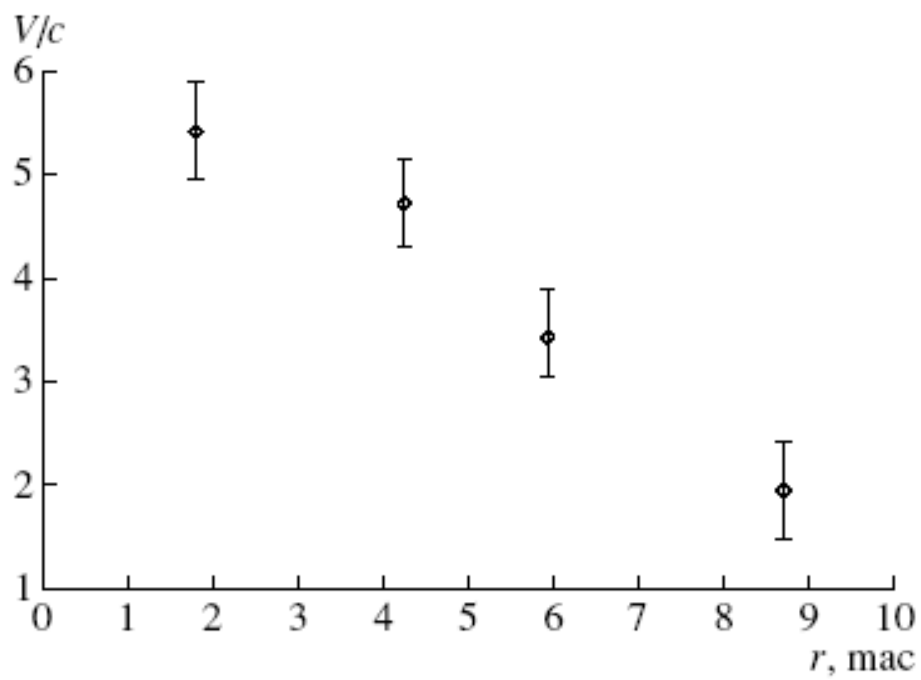


Fig. 6. Apparent speeds of the jet knots as a function of distance from the radio core.